

Nucleon Resonance Transition Formfactors

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We discuss recent results from CLAS on electromagnetic resonance transition amplitudes and their dependence on the distance scale (Q^2). From the comparison of these results with most advanced theoretical calculations within QCD-based approaches there is clear evidence that meson-baryon contributions are present and important at large distances, i.e. small Q^2 , and that quark core contributions dominate the short distance behavior.

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1 Introduction

The excited states of the nucleon have been studied experimentally since the development of the quark model in 1964 [1, 2]. The 3-quark structure of the baryons when realized in the dynamical quark models resulted in prediction of a wealth of excited states with underlying spin-flavor and orbital symmetry of $SU(6) \otimes O(3)$. Most of the initially observed states were found with hadronic probes. From the many excited states predicted by the quark model, only a fraction have been observed to date. The search for the "missing" states and detailed studies of the resonance structure is now mostly carried out using electromagnetic probes and has been a major focus of hadron physics for the past decade [3]. This has led to a broad experimental effort and the measurement of exclusive meson photoproduction and electroproduction reactions, including many polarization observables. As a result, several new excited states of the nucleon have been discovered and entered in the Review of Particle Physics [4].

Meson electroproduction, which is the subject of this talk, has revealed intriguing new information regarding the relevant degrees of freedom underlying the structure of the excited states at different distance scale probed [5].

2 The $N\Delta(1232)$ transition

One of the important insights is clear evidence that resonances are not excited from quark transitions alone, but there can be significant contributions from meson-baryon interactions as well, and that these two processes contribute to the excitation of the same state. This evidence has been obtained in part through the observation that the quark transition processes often do not have sufficient strength to explain fully the measured resonance transition amplitudes. The best known example is the $\Delta(1232)3/2^+$ resonance, which, when excited electromagnetically is mostly due to a magnetic dipole transition from the nucleon ground state, but only a fraction of the magnetic transition form factor can be explained by the quark content of the state at the photon point. Instead, at $Q^2 \geq 3 \text{ GeV}^2$ the quark content becomes the biggest contributor to this transition form factor. At low Q^2 a satisfactory description of this transition can be achieved in models that include pion-cloud contributions and also in dynamical reaction models, where the missing strength has been attributed to dynamical meson-baryon interaction in the final state [6].

A recent calculation within the light front relativistic quark model (LF RQM) [7, 9] with the 3-quark contributions that are normalized to the high Q^2 behavior finds that at the photon point more than 50% of the strength may be due to non-quark contributions, as shown in Fig. 1. The excitation of this and other states using electron beam should be highly sensitive to the different Fock components in the wave function of the excited states as it is expected that they have different excitation strengths when probed at large and at short distance scales, i.e. with virtual photons at low and high Q^2 . At

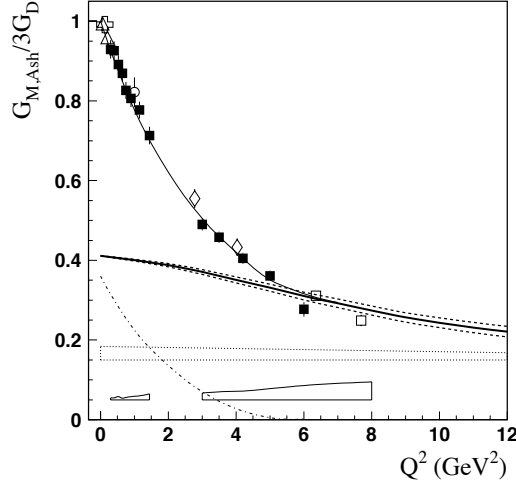


Figure 1: The magnetic transition form factor G_M^* of the $N\Delta(1232)$ transition as determined in various experiments and analyses of $ep \rightarrow ep\pi^0$. The thin solid line is the global analysis of Ref. [8]. The 3-quark contributions in the LF RQM (solid line with dotted error band) is normalized to the high Q^2 behavior. The open band at the bottom shows the model uncertainties of the extracted data points. The band above it represents the uncertainties of the model analysis [9]. The thin dash-dotted line is the estimated meson-baryon contribution from Ref. [10].

high Q^2 we expect the qqq components to be the only surviving part, while the higher Fock states may have large, even dominant strength at low Q^2 .

3 Solving the Roper puzzle

It is known that the Roper $N(1440)\frac{1}{2}^+$ state presented the biggest puzzle of the well-established resonances and defied explanations within the quark model for decades. The constituent quark model has it as the first radial excitation of the nucleon ground state. However, its physical mass is about 300 MeV lower than what is predicted. The most recent LQCD projections have the state even 1 GeV above the nucleon ground state, i.e. near 1.95 GeV [11]. The electromagnetic transition amplitude extracted from pion photo production data is large and negative, while the non-relativistic constituent quark model (nrCQM) predicts a large and positive amplitude. Furthermore, the early electroproduction results showed a rapid disappearance of its excitation strength at $Q^2 \leq 0.5 \text{ GeV}^2$, while the model predicted a strong rise in magnitude. These apparent discrepancies led to attempts at alternate interpretations of the state, e.g. as the lowest gluonic excitation of the nucleon [12], and as dominantly $N\rho$ [13] or $N\sigma$ [14] molecules. Recent development of the dynamically coupled channel models by the EBAC group, has led to a possible resolution of the discrepancy in the mass values, by including resonance

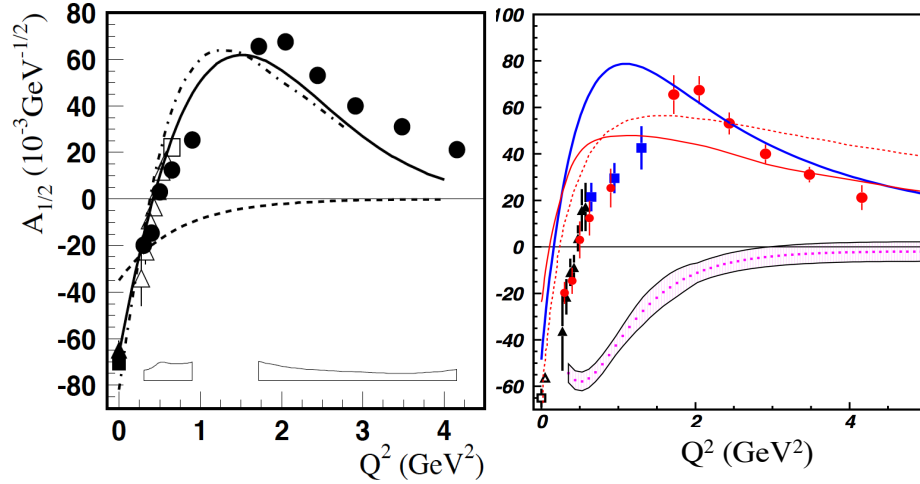


Figure 2: The transverse electrocoupling amplitude $A_{1/2}(Q^2)$ for the Roper $N(1440)_{\frac{1}{2}}^{+}$. The panel on the left shows the CLAS data as of 2012 [18, 19]. The curves are non-relativistic quark model calculations that include $N\sigma$ configurations [20]. The dashed line is the $N\sigma$ contribution, the solid line is the full result. At high Q^2 the model undershoots the data significantly. The right panel includes also recent data from $p\pi^+\pi^-$ final states [21] (blue squares). The red curves are LF RQM calculations with $N\sigma$ components [22] (dashed), and with momentum-dependent quark masses [7] (solid). The blue curve is the DSE/QCD calculation [23] after renormalization of the quark wave function [21]. The band in the lower part represents the difference of the DSE/QCD predictions and the CLAS data.

coupling to inelastic decay channels in their calculations [15]. The inelastic channels caused the dressed Roper pole to move by over 350 MeV close to 1.365 GeV from the bare value of 1.736 GeV, i.e. close to where it is found experimentally. Measurements of the electro-coupling amplitudes in large range of Q^2 [16, 17, 18] provided strong evidence for the Roper resonance as a predominantly first radial excitation of a nucleon ground state. The electrocoupling amplitudes are shown in Fig. 2. The LF RQM predict correct sign of the transverse amplitude at $Q^2 = 0$ and a sign cross-over at small Q^2 . The behavior at low Q^2 is described well when the 3q component in the wave function is complemented by meson-baryon contributions, e.g. $N\rho$ [13] and $N\sigma$ [20], and also in effective field theories [24] employing pions, ρ mesons, the nucleon and the Roper $N(1440)_{\frac{1}{2}}^{+}$ as effective degrees of freedom. The high Q^2 behavior is well reproduced in the QCD/DSE approach and the LF RQM which include momentum-dependent quark masses, in QCD/DSE [23] due to full incorporation of the momentum-dependent dressed quark mass in QCD and in LF RQM [7] by a parameterized mass function.

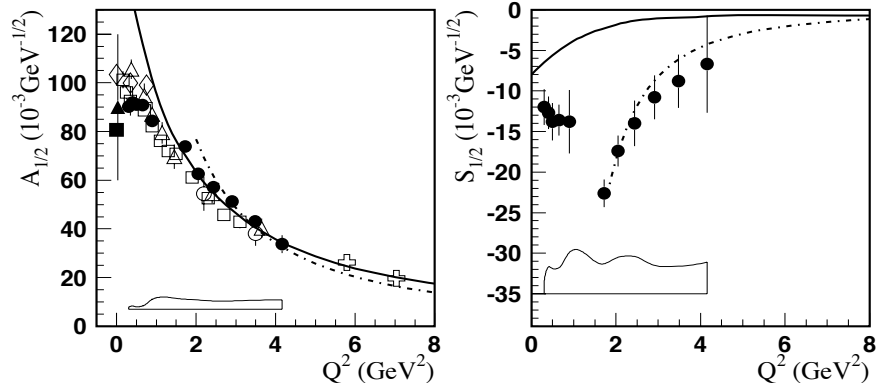


Figure 3: The transverse and scalar amplitudes for the $N(1535)\frac{1}{2}^-$ determined in $ep \rightarrow ep\eta$ (open symbols) and in $ep \rightarrow eN\pi$ (full circles). The open bands indicate the size of model-dependency in the extraction of the resonance amplitudes. Curves represent LF RQM (solid), and LC SR (dashed-dotted).

4 The parity partner of the nucleon $N(1535)\frac{1}{2}^-$

The parity partner of the ground state nucleon lies 600 MeV above the mass of the nucleon. The shift is thought to be due to the breaking of chiral symmetry in the excitation of nucleon resonances. The state has been difficult to interpret in terms quark excitations only, especially the sign and Q^2 -dependence of its scalar amplitude. Figure 3 shows both $A_{\frac{1}{2}}$ and $S_{\frac{1}{2}}$ transition amplitudes. $A_{\frac{1}{2}}$ is well described by the LF RQM [7] and the LC SR (NLO) [25] evaluation for $Q^2 \geq 1.5\text{GeV}^2$. The scalar amplitude $S_{\frac{1}{2}}$ departs from the LF RQM predictions significantly, it is, however, well described by the LC SR (NLO) calculation at $Q^2 \geq 1.5\text{GeV}^2$. The lowest moments of the $N(1535)\frac{1}{2}^-$ quark distribution amplitudes fit to the electrocoupling data are consistent with the values computed in LQCD [25]. This result points at a promising approach of relating the resonance electrocouplings to calculations from first principle of QCD. The state has also been discussed as having large strangeness components [26], an assertion that might account for the discrepancy in the scalar amplitude with the data at low Q^2 .

5 Transverse LF charge transition densities.

Knowledge of the electrocoupling amplitudes in a large range of Q^2 allows for the determination of the transition charge densities in the light front [27]. Such densities have been obtained for the $\Delta(1232)\frac{3}{2}^+$ where data are available from the photon point to $Q^2 \approx 7.0\text{GeV}^2$ for all 3 electrocoupling amplitudes and for states in the second nucleon resonance region. Fig. 4 shows the charge transition densities based on new fits to the

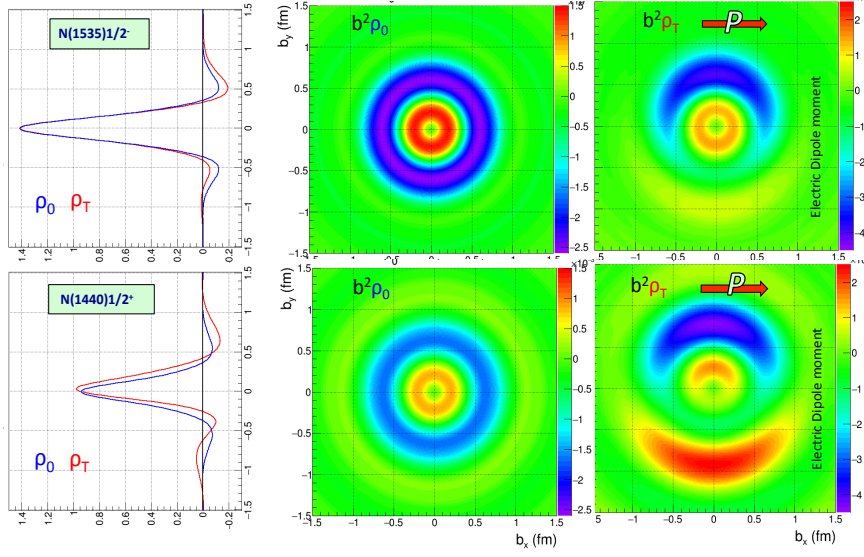


Figure 4: The transverse charge transition densities of the $N(1440)\frac{1}{2}^+$ and $N(1535)\frac{1}{2}^-$ using the definition of ρ_0 and ρ_T in Ref. [27]. For comparison of the two states, the same scales have been used in all graphs. The two left panels show the charge densities projected on the b_y axis; ρ_0 (blue line) is for unpolarized protons, ρ_T for transversely polarized protons. The 2-D plots on the right show the b_x versus b_y correlations of the ρ_0 (middle) and ρ_T (right) transition densities. To emphasize the large distance behavior the densities have been scaled with b^2 causing the hole in the center.

$A_{1/2}(Q^2)$ and $S_{1/2}(Q^2)$ of the $N(1440)\frac{1}{2}^+$ and $N(1535)\frac{1}{2}^-$ electrocoupling amplitudes. This allowed the extraction of transition charge densities for the unpolarized nucleon to the excited state, and for the transversely polarized proton to the excited states. One would expect that the charge densities are different for the two states as one is a radial excitation of the nucleon, the other an orbital excitation of the quark core. There is indeed a notable difference between the two states. The Roper $N(1440)$ shows a considerably softer core and wider wings compared to the $N(1535)$. Furthermore, the peak in the $N(1440)$ charge distribution for the polarized proton moves away from the center to more positive b_y generating a strong electric dipole along b_y , while the $N(1535)$ core shows no change in position.

6 New results on states in the 1.7 GeV mass range

Cross sections on $ep \rightarrow e\pi^+n$ have been published recently in the mass range from 1.6 to 2.0 GeV [28]. The so-called third resonance regions is the domain of several nearly mass degenerate states with masses near 1.7 GeV. Several states, e.g. $N(1675)\frac{5}{2}^-$ and $N(1650)\frac{1}{2}^-$ belong in $SU(6) \otimes O(3)$ to the $[70, 1^-]_1$ supermultiplet, while the $N(1680)\frac{5}{2}^+$ quark state is assigned to $[56, 2^+]_2$. The assignment to different multiplets within that symmetry group has important impact on the transition strength of the 3-quark com-

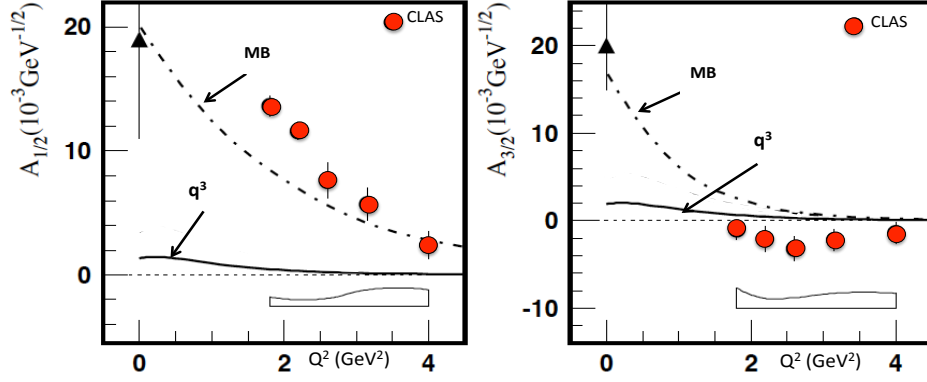


Figure 5: The transverse amplitudes of the $N(1675)_{1/2}^{5-}$ have been determined in $ep \rightarrow e\pi^+n$ (for references see text).

ponents in the excited states. Depending on the multiplet assignment, we may expect quite different strengths and Q^2 dependences of the quark components. For example, the quark structure of the $N(1675)_{1/2}^{5-}$ leads to a suppressed 3-quark transition amplitude from the proton, i.e. $A_{1/2}^q = A_{3/2}^q = 0$. We employed this suppression to directly access the non-quark components [29]. The results for the $N(1675)_{1/2}^{5-}$ are shown in Fig. 5. The constituent quark model predictions are from Ref. [30]. Shown predictions for the meson-baryon (MB) contributions are absolute values of the results from the dynamical coupled-channel model (DCCM) [31]. They are in qualitative agreement with the amplitudes extracted from experimental data, i.e. considerable coupling through the $A_{1/2}$ amplitude and much smaller $A_{3/2}$ amplitude at $Q^2 \geq 1.8 \text{ GeV}^2$. Figure 6 shows the results for the $N(1680)_{1/2}^{5+}$ resonant state. There is a rapid drop with Q^2 of the $A_{3/2}$ amplitude, which dominates at $Q^2 = 0$, while the $A_{1/2}$ amplitude, which at $Q^2 = 0$ makes a minor contribution, becomes the leading amplitude at larger Q^2 . This change of the helicity structure is expected, but it is less rapid than predicted by quark models, which could hint at sizable meson-baryon contributions at large Q^2 .

7 Conclusions

The meson electroproduction program at Jefferson Lab has revealed that many excited states predicted within the symmetry group $SU(6) \otimes O(3)$ have higher Fock state components that can be represented by meson-baryon components in the wave function. Most states in the mass range up to 1.7 GeV exhibit the common feature that the excitation strengths of the higher Fock states components decrease more rapidly with increasing Q^2 than the leading qqq components. At $Q^2 \geq 2 - 3 \text{ GeV}^2$ the qqq components dominate and closely follow the LF RQM calculations [7] and the projections of DSE/QCD [23] and NLO LCSR [25]. The results on the Roper resonance $N(1440)_{1/2}^{1+}$ clearly establish the state as the first radial excitation of the nucleon's 3-quark core. The most recent theoretical developments successfully explored new avenues towards relating resonance electrocouplings to the first principles of QCD.

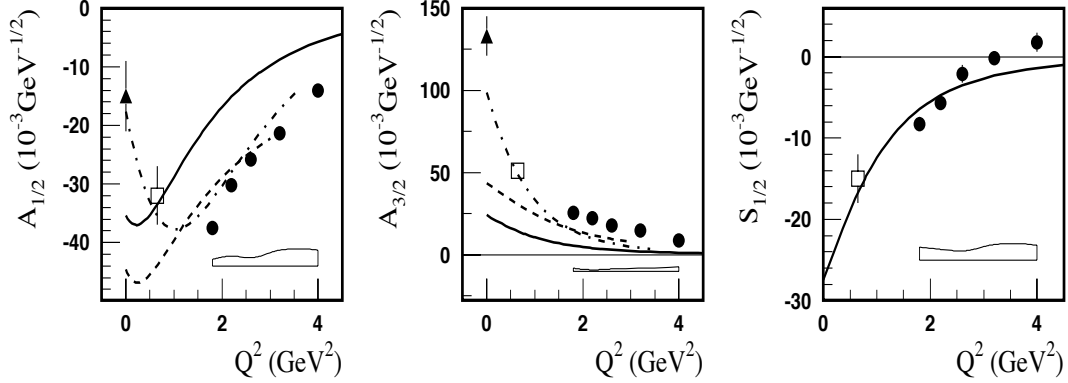


Figure 6: The transverse and scalar amplitudes for the $N(1680)_{\frac{5}{2}}^{+}$ determined in $ep \rightarrow e\pi^{+}n$. The curves are projections of various quark models.

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